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Low-spin studies of the $\pi h_{11/2} \nu h_{11/2}$ structure in ^{134}Pr

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Low-spin states built on the $\pi h_{11/2} \nu h_{11/2}$ configuration in ^{134}Pr have been studied using a ^{119}Sn(^{19}F,4n) fusion-evaporation reaction. A planar low-energy photon spectrometer along with a low-Z target chamber was utilized in an array of five high-purity Ge detectors for the purpose of measuring low-energy γ rays. A 39.3-keV γ ray was discovered as a new transition at the bottom of the band. The transition was found to have an $M1$ multipolarity, determined from the internal conversion coefficients evaluated from the missing transition intensity. The new bandhead was assigned and was identified as an isomeric state with a mean lifetime of $\tau = 4.6(1)$ ns. This bandhead decays by a 306-keV γ-ray transition that was found to have an $E1$ multipolarity through the analysis of the angular distribution asymmetry.

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Odd-odd nuclei in the triaxial mass ($A \sim 130$) region have been investigated recently in search of predicted chirality [1] in angular momentum coupling. As expected, $\pi h_{11/2} \nu h_{11/2}$ doublet band structures were identified in a number of $N=75$ [2–4], $N=73$ [5], and $N=77$ [6] isotones. Among these nuclei, ^{134}Pr provides so far the best example of level degeneracy for selected states of the same spin and parity in the doublet bands being separated by energies smaller than 60 keV. Although existing information on relative spins and parities is sufficient to investigate the doubling of states resulting from nuclear chirality, the quest of absolute spin/parity assignments should be pursued if detailed comparisons with theoretical calculations are to be made; thus reliable data on the decay properties near the bandhead is of importance. Such information, however, is often unavailable due to the well known difficulties encountered in the studies of odd-odd nuclei, resulting from the occurrence of isomeric decays or the existence of low-energy γ-ray transitions which are attenuated and are often below observation sensitivity thresholds for typical experiments. Indeed, systematic studies of Ref. [7] supported by the recent experimental data from the ^{116}Cd (^{23}Na,5n) ^{134}Pr Gammasphere experiment [8] suggest that the level scheme at low spins as proposed in Refs. [9,10] is incomplete. This observation motivated a reinvestigation of the low-spin part of the $\pi h_{11/2} \nu h_{11/2}$ doublet band as reported in the current paper with an appropriate apparatus of sufficient sensitivity in the low-energy part of the γ-ray spectrum.

The ^{134}Pr nucleus was populated via the ^{119}Sn (^{19}F,4n) reaction with a beam energy of 76 MeV. The beam was provided by the Stony Brook FN-tandem/superconducting LINAC facility. The target consisted of a 6.8 mg/cm^2 ^{119}Sn foil backed with 58 mg/cm^2 evaporated natural Pb. The emitted γ rays were observed through a $\sim$1-mm-thick glass target chamber that was designed for the purpose of measuring very low γ-ray energies that metal target chambers generally attenuate. Measurements were made using an array of five Compton-suppressed high-purity germanium (HPGe) coaxial detectors, and a single 5-mm planar low-energy photon spectrometer (LEPS) detector with a beryllium window, which was implemented for low-energy γ-ray measurements. The HPGe detectors were positioned at $\sim \pm 30$, ± 90, and $+150°$ relative to the beam axis. The LEPS was positioned at $\sim -150°$. All detectors were used in conjunction with a 14-element BGO multiplicity filter, allowing for the selection of events with a multiplicity of 2 or higher. Electronic lifetime measurements were made by employing a pulsed beam with a repetition rate of 106 ns and a width of less than 1 ns. Time spectra were collected using a time-to-amplitude converter (TAC) for all observed γ rays for each individual detector. Data were stored onto magnetic tape event by event for off-line analysis. Coincidence data were sorted off-line into an asymmetric $E_\gamma - E_\gamma$ matrix with the HPGe and LEPS detectors incremented on the y axis and x axis, respectively. One-dimensional LEPS spectra gated by the HPGe detectors were projected from the matrix. These spectra were used to identify low energy γ-ray transitions between members of the $\pi h_{11/2} \nu h_{11/2}$ yrast band in ^{134}Pr. Pulsed beam data were sorted into asymmetric matrices, with E_γ and TAC data incremented on the y axis and x axis, respectively. One-dimensional TAC spectra gated by E_γ were obtained for each individual detector.

Multipolarities for low-energy transitions were assigned based on electronic conversion coefficients evaluated from missing intensities in the observed experimental spectra. Several gates were selected, which assured that the total intensities for the investigated transitions and the compared coincident transition were equal. The electron conversion coefficient for the transition of interest was then measured based on the difference between its observed γ-ray intensity and evaluated total intensity. The LEPS spectra used for the intensity measurements were calibrated for efficiency using a ^{133}Ba source. For transitions that correspond to high-energy γ rays, where electron conversion is negligible, multipolarities were assigned based on the measured asymmetries of the $W(30°)/W(90°)$ angular distribution ratio [11].

All analyses were aided by the use of the RADWARE [12] γ-ray spectroscopy software package.

The decay scheme for the $\pi h_{11/2} \nu h_{11/2}$ structure at a low

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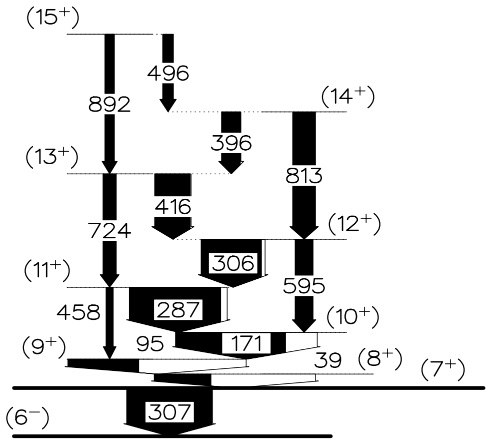

FIG. 1. Decay scheme for the $\pi h_{11/2}\nu h_{11/2}$ structure at low spin in ^{134}Pr.

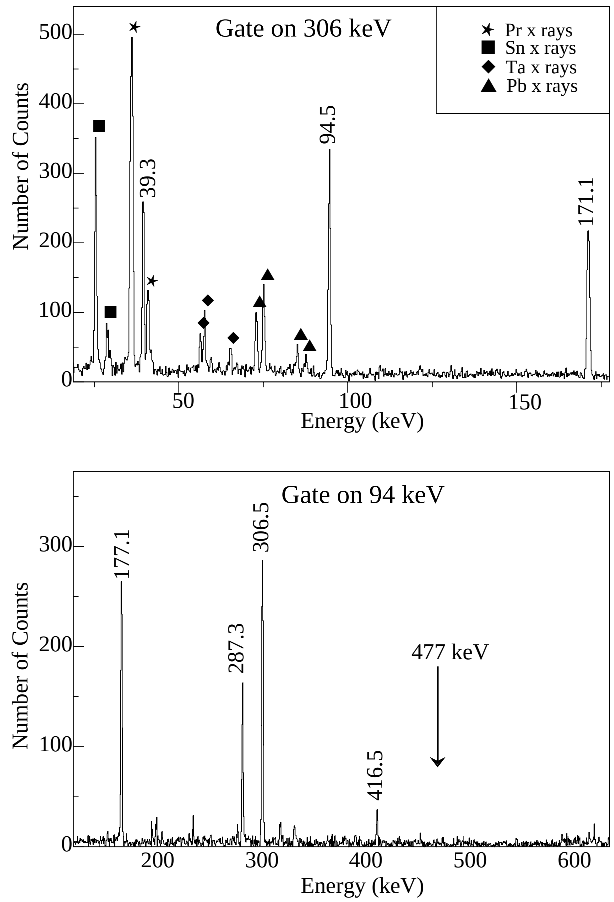

FIG. 2. LEPS spectrum gated on the 306-keV γ ray. The 39.3-, 94.5-, and 171.1-keV transitions belonging to ^{134}Pr are shown. X rays of Pr, Sn, Ta, and Pb are marked with asterisks, squares, diamonds, and triangles, respectively. The 94-keV gated spectra show the absence of a 477-keV γ ray previously reported.

spin resulting from the current work is shown in Fig. 1. This level scheme differs from that proposed in Ref. [10], where a 307-keV transition was assigned to be an in-band transition with multipolarity $M1$, and the existence of a 477-keV $E2$ crossover was reported in parallel to the 171–307 keV cascade. In the present work, the 477-keV transition was not observed, while the low-energy γ-ray measurements performed with the LEPS detector indicate the existence of a 39-keV γ ray in coincidence with the transitions of the $\pi h_{11/2}\nu h_{11/2}$ band in ^{134}Pr. Indeed, a peak at 39 keV is clearly observed in the LEPS spectrum gated on the 306-keV γ ray as shown in Fig. 2, together with peaks for band members with 95 and 171 keV. The peaks at low energies other than that of 39 keV are identified as x rays of Pr, Sn, Pb, and Ta [13], and are marked accordingly in the inset. The presence of Sn, Pb, and Ta x rays is understood as resulting from fluorescence of the target, the target backing, and the target frame, respectively. The 39-keV γ ray is not observed in spectra that are gated on transitions in other isotopes populated in the reaction, namely, ^{133}Pr and ^{135}Pr. Therefore, it has to be associated with the deexcitation of the $\pi h_{11/2}\nu h_{11/2}$ band of interest. Following the decay pattern observed for the $\pi h_{11/2}\nu h_{11/2}$ structure with transition energies decreasing with decreasing spin/excitation energy, it is proposed that the 39-keV γ ray is the new in-band transition below the 95-keV γ ray as shown in Fig. 1. This assignment is supported by the electron conversion coefficient measurements summarized in Table I, which yield $M1$ multipolarities for the 39- and 95-keV transitions in the $\pi h_{11/2}\nu h_{11/2}$ band in ^{134}Pr.

The γ ray at 306 keV was identified as a doublet in Ref. [10]. This conclusion is confirmed in the present study, however, the electronic transition lifetime measurement indicates that one of the components of the doublet is an isomer. The analysis of the time-gated LEPS energy spectrum yields energies of 306.3$\pm$0.1 and 306.5$\pm$0.1 keV for prompt and delayed components of the doublet, respectively. The time spectrum measured with the LEPS detector, which corresponds to the 306-keV doublet is shown in Fig. 3. The τ =4.6(1) ns lifetime was extracted from this spectrum using a least squares fit method. The fitted function included a prompt component with a Gaussian shape, an exponential decay convoluted with the prompt function, and a linear background. The resulting best fit which corresponds to the extracted lifetime is shown in Fig. 3, together with the prompt resolution function measured by gating on a pulse-height region near the 306-keV peak. The analysis of the LEPS time spectra corresponding to 39-, 95-, and 171-keV transitions indicates lifetime slopes shorter than the $\sim$1 ns sensitivity of the current measurement. As a consequence, the delayed component of the 306-keV doublet has to be placed in the decay scheme below the 39-, 95-, and 171-keV band members as shown in Fig. 1. The asymmetry of the angular distribution for the delayed component of the 306-keV doublet extracted from the time gated HPGe spectra,

TABLE I. Internal conversion coefficients.

	Theoretical[a]				
E_γ (keV)	$E1$	$E2$	$M1$	$M2$	Experimental
39.3	0.836	83.1	4.88	201.0	3.64$\pm$0.38
94.5	0.308	2.83	1.64	17.6	1.40$\pm$0.32

[a]Reference [14].

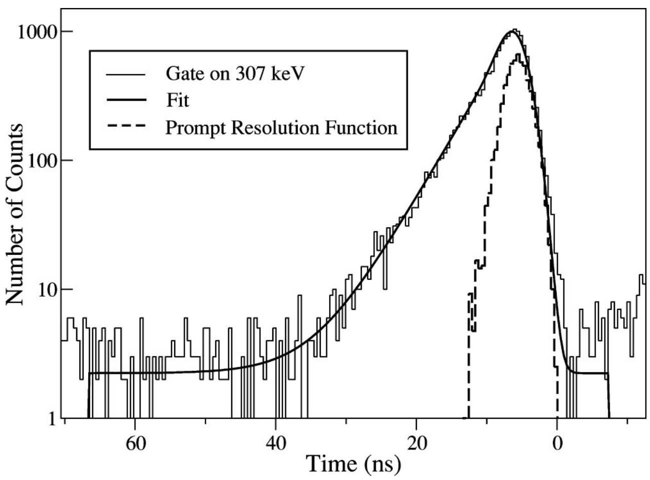

FIG. 3. Time spectrum gated on the 306-keV γ ray from the LEPS time-energy matrix. The fit to the data and a measured prompt resolution function have been overlayed.

$W(30°)/W(90°)=0.6(2)$, is consistent with the theoretical asymmetry of 0.76 calculated assuming pure stretched dipole character for this transition. A dipole character for both components of the 306-keV doublet was proposed in Ref. [10], both with $M1$ multipolarity assignments. In the present work, however, it is proposed that the delayed component of the 306-keV doublet is an $E1$ transition, which corresponds to the configuration change from $\pi h_{11/2}\nu h_{11/2}$ for the initial state into $\pi(d_{5/2}g_{7/2})\nu h_{11/2}$ for the final state. The $\pi h_{11/2} \rightarrow \pi(d_{5/2}g_{7/2})$ $E1$ transition is forbidden in spherical nuclei by the selection rules for the $E1$ operator, but in deformed nuclei, the $\pi h_{11/2}$ orbital picks up $f_{7/2}$ and $h_{9/2}$ components, while $\pi(d_{5/2}g_{7/2})$ picks up $g_{9/2}$ components that allow for $E1$ transitions. Since these admixtures are necessarily small, the resulting $E1$ matrix element is small as well, which explains the relatively long lifetime. With this assignment, the isomeric state becomes the bandhead for the $\pi h_{11/2}\nu h_{11/2}$ structure. Unlike neighboring nuclei with similar structures, which show multiple decays from the bandhead [15], this 306-keV isomer is the only decay observed from the $\pi h_{11/2}\nu h_{11/2}$ band.

The multipolarity assignment discussed above for the new 39-keV γ ray and the isomeric 307-keV transition yield relative spins/parities only. For absolute assignments, firm knowledge of spin/parity for one of the observed states is required. This information is not yet available in ^{134}Pr. The tentative spins/parities proposed in Fig. 1 are adopted based on experimental systematics developed in Ref. [7] for the mass-130 region. With these assignments, the lowest state observed in the experiment has a spin/parity of (6^-), and is a very likely candidate for the $\tau=11$ min isomer that β decays to high-spin states in ^{134}Ce, as identified in Ref. [16]. In the original work [16] which reported the existence of the isomer, a (5^-) assignment was proposed for the spin/parity based on the observed β^+ decay pattern and deduced log(ft) values. A recent measurement with improved sensitivity [17] led to the identification of ^{134}Ce states with higher spins than those reported in Ref. [16], which were populated in the β^+ decay of ^{134}Pr; this resulted in the proposed (7^-) assignment for the spin/parity of the isomeric state in ^{134}Pr. Taking into account the difficulties involved in studies of odd-odd nuclei, the presently proposed (6^-) assignment is reasonable, although further study is necessary for an unambiguous spin/parity measurement.

The bandhead spin (7^+) for the $\pi h_{11/2}\nu h_{11/2}$ band suggests nearly orthogonal coupling of the angular momenta for the valence proton and neutron. Indeed, if this is the case, an expected spin for the bandhead is $\sqrt{j_\pi^2+j_\nu^2}\sim 7.7\hbar$ for $j_\pi = j_\nu = 11/2$, assuming no contribution from all paired nucleons of the core. The orthogonal coupling of angular momenta for valence nucleons is a necessary condition for the observation of chiral doublets in triaxial odd-odd nuclei, and indeed such doublets were identified at higher spins in ^{134}Pr in Refs. [2,8,10].

In summary, the decay pattern of the ^{134}Pr $\pi h_{11/2}\nu h_{11/2}$ band structure at low spins was studied in detail using in-beam γ-ray spectroscopy techniques. A LEPS detector was employed for identification of the low-energy γ rays. A new in-band transition with an energy of 39 keV was observed, while a previously reported 306-keV transition was identified as an isomeric transition. Multipolarities of the observed γ rays were assigned based on the measured electron conversion coefficients and the angular distribution asymmetry. A new decay scheme for the $\pi h_{11/2}\nu h_{11/2}$ band at a low spin is proposed with the isomeric transition interpreted as resulting from the $\pi h_{11/2}\nu h_{11/2} \rightarrow \pi(d_{5/2}g_{7/2})\nu h_{11/2}$ configuration change. An adopted absolute spin assignment suggests (7^+) for the bandhead of the $\pi h_{11/2}\nu h_{11/2}$ structure. This is consistent with orthogonal coupling of angular momenta for the valence nucleons, which is a necessary condition for the observation of chiral doublets at higher spins for this nucleus in the triaxial transitional $A\sim 130$ region.

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